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Anomalous Quartic Couplings in $\nu\bar{\nu}\gamma\gamma$ Production via WW-Fusion at LEP2

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Abstract

The production of $\nu\bar{\nu}\gamma\gamma$ in high-energy e^+e^- collisions offers a window on anomalous quartic gauge boson couplings. We investigate the effect of two possible anomalous couplings on the cross section for $\nu\bar{\nu}\gamma\gamma$ production via WW-fusion at LEP2 ($\sqrt{s} = 200$ GeV).

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1 Introduction

In the Standard Model (SM), the couplings of the gauge bosons and fermions are tightly constrained by the requirements of gauge symmetry. In the electroweak sector, for example, this leads to trilinear VVV and quartic $VVVV$ interactions between the gauge bosons $V = \gamma, Z^0, W^\pm$ with completely specified couplings. Electroweak symmetry breaking via the Higgs mechanism gives rise to additional Higgs – gauge boson interactions, again with specified couplings.

The trilinear and quartic gauge boson couplings probe different aspects of the weak interactions. The trilinear couplings directly test the non-Abelian gauge structure, and possible deviations from the SM forms have been extensively studied in the literature, see for example [1] and references therein. Experimental bounds have also been obtained [2]. In contrast, the quartic couplings can be regarded as a more direct window on electroweak symmetry breaking, in particular to the scalar sector of the theory (see for example [3]) or, more generally, on new physics which couples to electroweak bosons.

In this respect it is quite possible that the quartic couplings deviate from their SM values while the triple gauge vertices do not. For example, if the mechanism for electroweak symmetry breaking does not reveal itself through the discovery of new particles such as the Higgs boson, supersymmetric particles or technipions it is possible that anomalous quartic couplings could provide the first evidence of new physics in this sector of the electroweak theory [3].

High-energy colliders provide the natural environment for studying anomalous quartic couplings. The sensitivity of a given process to anomalous quartic couplings depends on the relative importance of SM contributions to the anomalous contribution, as we shall see.

In this study we shall focus on e^+e^- collisions, and quantify the dependence of the WW-fusion $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ cross section on the anomalous couplings. Here we do not consider contributions from $e^+e^- \to Z\gamma\gamma \to \nu\bar{\nu}\gamma\gamma$ but refer to [4] where $e^+e^- \to Z\gamma\gamma$ is studied in detail. Note that in practice the anomalous contributions arising from WW-fusion and those from the resonant Z can be added with no danger of double counting, since the anomalous vertex is $WW\gamma\gamma$ in the former case and $ZZ\gamma\gamma$ in the latter. We shall consider in particular $\sqrt{s} = 200$ GeV corresponding to LEP2, and comment on the effect of increasing the collider energy.

Note that our primary interest is in the so-called 'genuine' anomalous quartic couplings, i.e. those which give no contribution to the trilinear vertices.

In the following section we review the various types of anomalous quartic coupling relevant for this analysis that might be expected in extensions of the SM. In Section 3 we present numerical studies illustrating the impact of the anomalous couplings on the WW-fusion $\nu\bar{\nu}\gamma\gamma$ cross sections. Finally in Section 4 we present our conclusions.

2 Anomalous gauge boson couplings

The lowest dimension operators which lead to genuine quartic couplings where at least one photon is involved are of dimension 6 [5, 4].

The neutral and the charged Lagrangians, both giving anomalous contributions to the $WW\gamma\gamma$ vertex, are

$$\begin{aligned}\mathcal{L}_0 &= -\frac{e^2}{16\Lambda^2}\,a_0\,F^{\mu\nu}\,F_{\mu\nu}\,\overrightarrow{W^{\alpha}}\cdot\overrightarrow{W_{\alpha}}\\ &= -\frac{e^2}{16\Lambda^2}\,a_0\,[\,-2(p_1\cdot p_2)(A\cdot A)+2(p_1\cdot A)(p_2\cdot A)]\\ &\qquad\qquad \times[2(W^+\cdot W^-)+(Z\cdot Z)/\cos^2\theta_w]\quad ,\end{aligned} \tag{1}$$

$$\begin{aligned}\mathcal{L}_c &= -\frac{e^2}{16\Lambda^2}\,a_c\,F^{\mu\alpha}\,F_{\mu\beta}\,\overrightarrow{W^{\beta}}\cdot\overrightarrow{W_{\alpha}}\\ &= -\frac{e^2}{16\Lambda^2}\,a_c\,[\,-(p_1\cdot p_2)\,A^{\alpha}A_{\beta}+(p_1\cdot A)\,A^{\alpha}p_{2\beta}\\ &\qquad\qquad +(p_2\cdot A)\,p_1^{\alpha}A_{\beta}-(A\cdot A)\,p_1^{\alpha}p_{2\beta}]\\ &\qquad\qquad \times[W^-_{\alpha}W^{+\beta}+W^+_{\alpha}W^{-\beta}+Z_{\alpha}Z^{\beta}/\cos^2\theta_w]\ .\end{aligned} \tag{2}$$

where p_1 and p_2 are the photon momenta and

$$\overrightarrow{W_{\mu}}=\begin{pmatrix}\frac{1}{\sqrt{2}}(W^+_{\mu}+W^-_{\mu})\\ \frac{i}{\sqrt{2}}(W^+_{\mu}-W^-_{\mu})\\ W^3_{\mu}-\frac{g'}{g}B_{\mu}\end{pmatrix}=\begin{pmatrix}\frac{1}{\sqrt{2}}(W^+_{\mu}+W^-_{\mu})\\ \frac{i}{\sqrt{2}}(W^+_{\mu}-W^-_{\mu})\\ \frac{Z_{\mu}}{\cos\theta_w}\end{pmatrix} \tag{3}$$

with $g'=\frac{e}{\cos\theta_w}$ and $g=\frac{e}{\sin\theta_w}$, originating from the requirement of a custodial $SU(2)$ symmetry to keep the ρ parameter, $\rho=M_W^2/(M_Z^2\cos^2\theta_w)$, close to its measured SM value of 1.

It follows from the Feynman rules that any anomalous contribution is *linear* in the photon energy E_{γ}. This means that it is the hard tail of the photon energy distribution that is most affected by the anomalous contributions, but unfortunately the cross section here is very small. In the following numerical studies we will impose a lower energy photon cut of $E_{\gamma}^{\min}=20$ GeV. Similarly, there is also no anomalous contribution to the initial state photon radiation, and so the effects are largest for centrally-produced photons. We therefore impose an additional cut of $|\eta_{\gamma}|<2$.[1]

Finally, the anomalous parameter Λ that appears in all the above anomalous contributions has to be fixed. In practice, Λ can only be meaningfully specified in the context of a specific model for the new physics giving rise to the quartic couplings. However, in order to make our analysis independent of any such model, we choose to fix Λ at a reference

[1]Obviously in practice these cuts will also be tuned to the detector capabilities.

value of M_W, following the conventions adopted in the literature. Any other choice of Λ (e.g. $\Lambda = 1$ TeV) results in a trivial rescaling of the anomalous parameters a_0 and a_c[2].

3 Numerical Studies

In this section we study the dependence of the $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ WW-fusion cross section on the two anomalous couplings defined in Section 2. Note that by 'WW-fusion' we mean the contribution of the Feynman diagrams shown in Fig. 1 to the cross section.

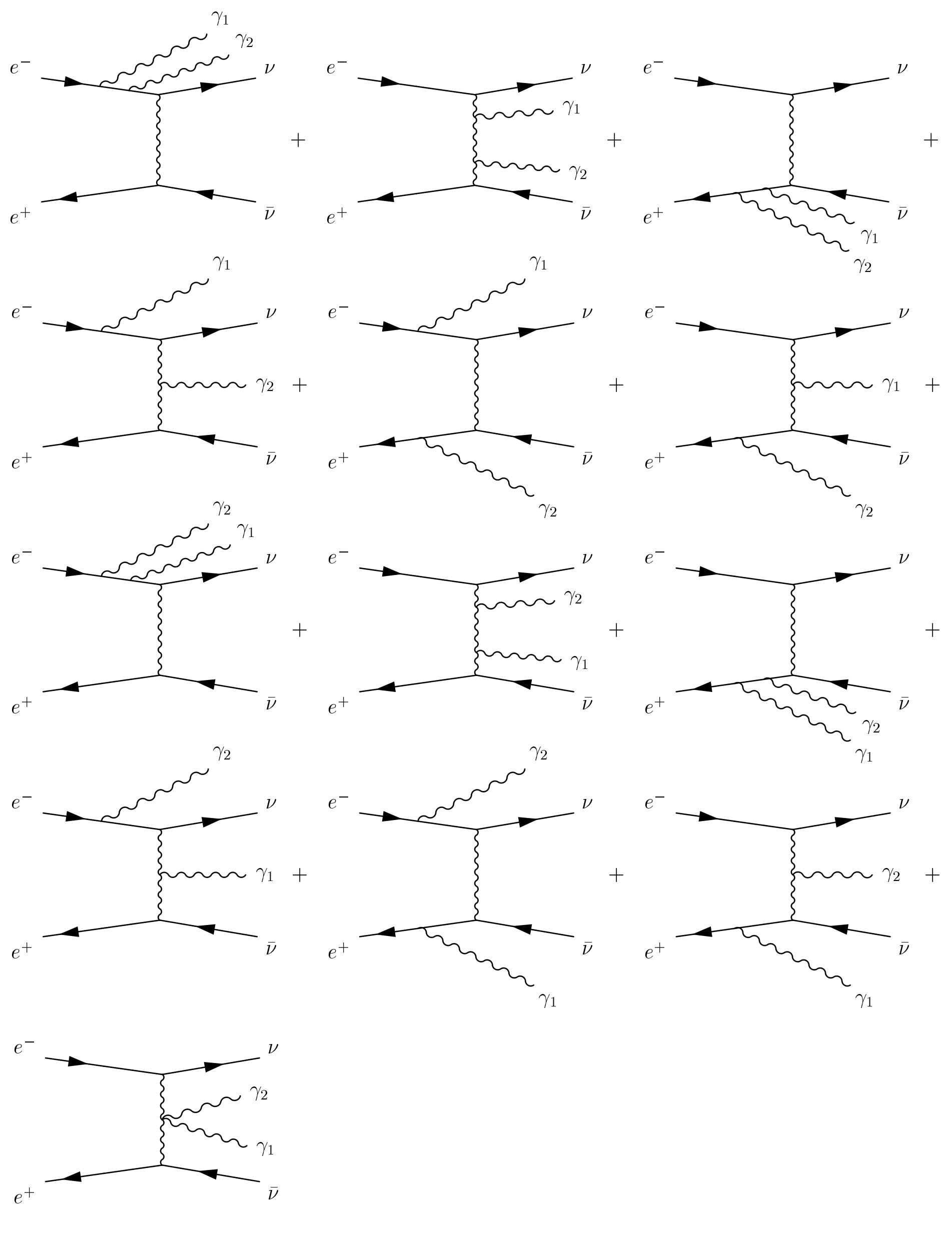

Figure 1: Feynman diagrams contributing to the WW-fusion $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ process.

[2]For a more detailed discussion of the parameter Λ we refer to [4].

The SM calculation is based on MADGRAPH [6]. As already stated, we apply a cut on the photon energy $E_\gamma > 20$ GeV to take care of the infrared singularity, and a cut on the photon rapidity $|\eta_\gamma| < 2$ to avoid collinear singularities.

As mentioned in the Introduction we do not include contributions from $e^+e^- \to Z\gamma\gamma \to \nu\bar{\nu}\gamma\gamma$, which obviously do not involve the $WW\gamma\gamma$ vertices. These have been studied in Ref. [4][3]. In practice, they can be straightforwardly removed by imposing cuts on the missing mass $M_{\nu\bar{\nu}}$ ($M_{\nu\bar{\nu}} < M_Z$). Nevertheless it has to be said that the $ZZ\gamma\gamma$ vertex has the identical anomalous structure, only the overall coupling is different.

We first consider the SM cross section for the process of interest, i.e. with all anomalous couplings set to zero. Figure 2 shows the collider energy dependence of the $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ WW-fusion cross section. In the LEP2 energy region the total cross section is O(1 fb).

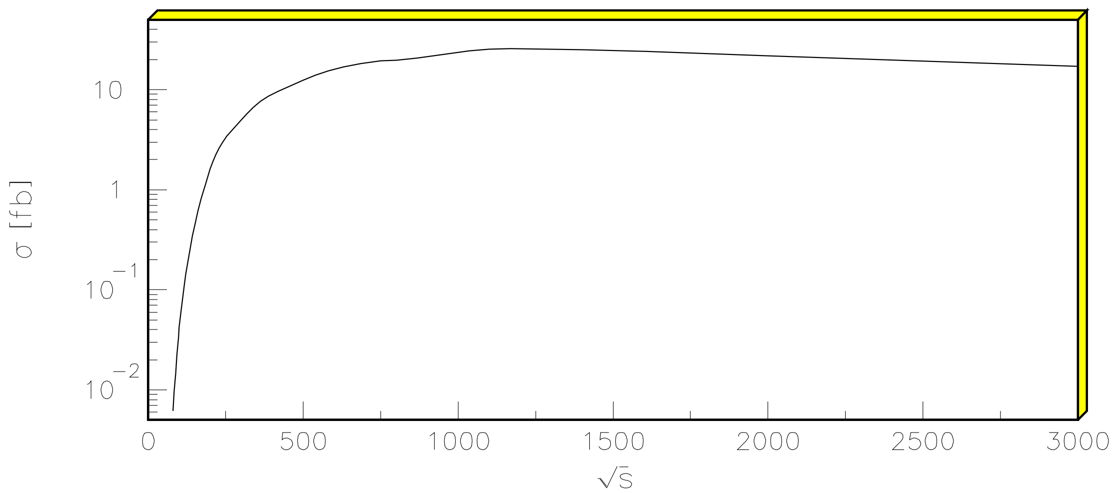

Figure 2: Total SM cross section for $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ via WW-fusion (in fb) as a function of $\sqrt{s}$ with $E_\gamma > 20$ GeV and $|\eta_\gamma| < 2$.

To study any anomalous effects on the total cross section we need to consider the *correlations* between the two different anomalous contributions.

To obtain quantitative results, we consider the experimental scenario of unpolarised e^+e^- collisions at 200 GeV with $\int \mathcal{L} = 150$ pb^{-1}.

Figure 3 shows the contours in the (a_0, a_c) plane that correspond to $+2, +3\,\sigma$ deviations

[3]Note that in Ref. [4] strictly $e^+e^- \to Z\gamma\gamma$ has been studied and for comparison with the present WW-fusion analysis the branching ratio $\Gamma(Z \to \nu\bar{\nu})$ has to be taken into account as well. This will result in weaker bounds due to the smaller cross section.

from the SM cross section at $\sqrt{s} = 200$ GeV.

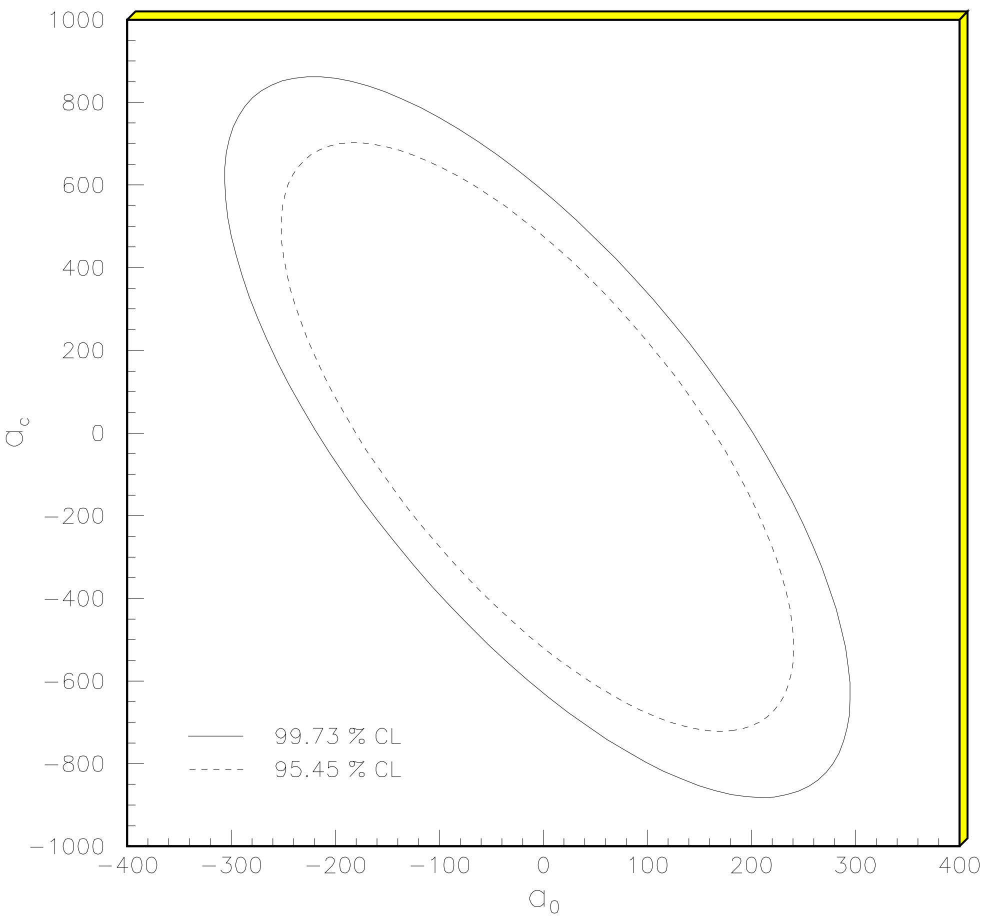

Figure 3: Contour plots for $+2, +3\,\sigma$ deviations from the WW-fusion SM $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ total cross section at $\sqrt{s} = 200$ GeV with $\int \mathcal{L} = 150$ pb^{-1}.

4 Discussion and Conclusions

We have investigated the sensitivity of the processes $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ via WW-fusion to genuine anomalous quartic couplings (a_0, a_c) at the canonical centre-of-mass energy $\sqrt{s} = 200$ GeV (LEP2). Key features in determining the sensitivity for a given collision energy, apart from the fundamental process dynamics, are the available photon energy E_γ, the ratio of anomalous diagrams to SM 'background' diagrams, and the polarisation state of the weak bosons [5].

From the purely phenomenological point of view the constraints obtained from this analysis are not competitive with those expected from analysing $WW\gamma$ production and especially from $Z\gamma\gamma$ production. The reason is that although the sensitivity to anomalous contributions is in general increased (i. e. lower ratio of SM-background to signal and increased phase space due to massless final states) the total cross section itsself is 2 orders of magnitude smaller than those for $WW\gamma$ production or $Z\gamma\gamma$ production. Thus with the relative small luminosity feasible for LEP2 there is little hope that advantages such as the particularly clean experimental environment will make up for the small cross section, and in that case we would expect the tighter bounds on the anomalous parameter to be obtained from analysing $Z\gamma\gamma$ production.

Nevertheless, since only massless particles are produced experimental data from basically any LEP2 centre of mass energy can be used to increase the overall integrated luminosity, and since the process *is* highly sensitive to anomalous couplings there is a chance that this process could actually in practice be leading to the tightest bounds. Of course in the end this can only be decided by a proper experimental data analysis.

For a future linear collider with for example $\sqrt{s} = 500$ GeV the process $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ becomes even less competitive, since at that energy the enlarged phase space of massless particles becomes even less important. Note also that at this energy the possibility of producing longitudinally polarised W, Z bosons does increase the sensitivity to anomalous couplings considerably [4]. In the WW-fusion process we do not have that opportunity since the Ws are bound to be 'internal' particles with no preferred polarization state.

Finally it is important to emphasise that in our study we have only considered 'genuine' quartic couplings from new six-dimensional operators. We have assumed that all other anomalous couplings are zero, including the trilinear ones. Since the number of possible couplings and correlations is so large, it is in practice very difficult to do a combined analysis of *all* couplings simultaneously.

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